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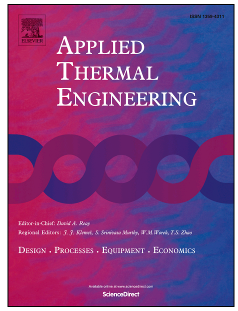

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Heat Transfer Enhancement by Combination of Chaotic Advection and Nanofluids Flow in Helically Coiled Tube

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Abstract.

In this study, two passive techniques are simultaneously investigated for heat transfer improvement (i.e. chaotic advection and nanofluids) in coiled heat exchangers. Performance of these two different coils (one with normal configuration and another with chaotic configuration) is numerically analyzed and compared for both water and nanofluid as fluid. Effects of different parameters such as geometry, types of nanofluids, nanoparticle volumetric concentration and Reynolds number on heat transfer and pressure drop are studied. The CuO and Al_2O_3 base water nanofluids with different nanoparticle concentrations 1-3% were simulated. Equations of conservation of mass, momentum and energy were discretized using a finite element based technique and were solved using ANSYS software. Numerical results showed that heat transfer in the chaotic coil with water as fluid was higher than that in the normal coil with nanofluids at various volumetric concentrations and addition small amount of nanofluid in the chaotic coil flow resulted in significant enhancement of heat transfer.

Keywords: Chaotic advection, Helical coiled Tube, Nanofluids, Pressure loss, Heat transfer

Nomenclature			
C_1	Constant	T_0	Constant Temperature [K]

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C_2	Constant	T_w	Wall Temperature [K]
C_3	Constant	T_b	Fluid Bulk Temperature [K]
C_4	Constant	u	Fluid Velocity [m.s^{-1}]
$C_{p,w}$	Water Specific Heat [J.kg^{-1}.K^{-1}]	U_m	Mean Velocity [m.s^{-1}]
d	Coil pipe diameter [m]	β	Brownian motion coefficient
d_{np}	Diameter of nanoparticle [m]	β_2	Brownian motion Constant
f	Friction factor	β_1	Brownian motion Constant
f_{nf}	friction factor of nanofluid	ε_1	Constant for Brownian Motion
f_w	friction factor of water	ζ_1	Constant
h	Convection Heat Transfer Coefficient [W.m^{-1}.K^{-1}]	ζ_2	Constant
h_w	convective heat transfer coefficient of water [W.m^{-1}.K^{-1}]	μ_w	Water Viscosity [Pa.s]
h_{nf}	convective heat transfer coefficient of nanofluid [W.m^{-1}.K^{-1}]	μ_{nf}	Dynamic Viscosity of the Nano Fluid [Pa.s]
k	Constant	ρ	Fluid Density [Kg.m^{-3}]
k_w	Water Thermal Conductivity [W.m^{-1}.K^{-1}]	ρ_{nf}	Nanofluid Density [Kg.m^{-3}]
k_{np}	Nano Particles Thermal Conductivity [W.m^{-1}.K^{-1}]	ρ_{np}	Nanoparticles Density [Kg.m^{-3}]
k_{nf}	Nanofluid Thermal Conductivity [W.m^{-1}.K^{-1}]	ρ_w	Water Density [Kg.m^{-3}]
P	Pressure [Pa]	τ_w	Shear Stress on the Wall [Pa]
q_w	Heat Flux [W.m^{-2}]	φ	Cylindrical coordinate

Re	Reynolds Number	Φ	Particle Volumetric Concentration [%]
T	Fluid Temperature [K]		

1. Introduction

In recent decades, many attempts have been undertaken for making efficient heat exchanging instruments in order to save energy and raw materials and consider economic and environmental issues. The main purpose has been to reduce size of the required heat exchanger for a specific heat load and also increase capacity of the existing one.

Convective heat transfer could be enhanced by increasing heat transfer area, mixing or thermal conductivity. Chaotic advection, which is production of chaotic particle paths in the laminar regime, is a passive technique for increasing heat transfer. Increase in mixing and heat transfer in the chaotic advection regime compared to the regular flow has been already established [1]. Chaotic mixing improves heat transfer by reducing temperature gradients and temperature profiles become more uniform. A signature of chaotic flows is that they are characterized by rapid divergence of fluid particles with close initial conditions. Stretching and folding exponentially increase in the chaotic flow and mixing is significantly enhanced. [2] chaotic mixers fall into one of two categories: 1) active mixers [3-6] that use moving parts and 2) passive mixers [7, 8] that utilize no energy input.

Chaotic coil flow is one of the passive mixers which has been addressed by Jones et al. [9], Acharya et al.[10, 11], Mokrani et al. [12], Castelain et al. [13, 14], Changy et al. [1], Kumar and Nigam [15, 16], Kumar et al. [17], Vashisth and Nigam [18] and Yamagashi et al. [19]. Normal coil flow generates a pair of vortices called Dean-roll-cells due to centrifugal force. Fluid particles could not escape from Dean-roll-cells; therefore, mixing and heat transfer decline in radial direction. In order to overcome this phenomenon, chaotic advection could be used by a simple geometrical perturbation in the chaotic coils by rotating axis of each coil with respect to the neighboring coil. Chaotic flow enables fluid particles to escape from trap of Dean-roll-cells by breaking and reassembling them.

Recently, the new science of nanofluids has been greatly considered. Metals in their solid phase have higher thermal conductivity than their fluid form. Nanofluids as a new category of passive techniques improve heat transfer through suspending nanoparticles in a fluid. The related literature contains studies about the number of coil heat exchangers that use nanofluids to enhance heat transfer. Akhavan et al. [20], Hashemi and Akhavan-Behabadi [21] and Fakoor et al. [22] have studied heat transfer and pressure drop characteristics of nanofluid flows inside the helical tube and concluded that, by using the helically coiled tube instead of the straight one, heat transfer performance is improved. Applying helical tube instead of the straight tube is a more effective way to enhance convective heat transfer coefficient than applying nanofluids instead of the pure liquid.

Sasmito et al. [23] numerically evaluated laminar heat transfer increase for a nanofluid flow in the coiled square tubes. Their results indicated that adding small amounts of nanoparticles up to 1% (volumetric concentration) significantly improved heat transfer performance.

Akbaridoust et al. [24] investigated steady state laminar nanofluid flow in helically coiled tubes at constant wall temperature both numerically and experimentally. They investigated pressure drop and convective heat transfer behavior of nanofluid and used homogeneous model with constant effective properties. Their results showed that utilization of base fluid in helical tube with greater curvature than using nanofluid in straight tubes more effectively enhanced heat transfer.

Mohammed and Narrein [25] investigated different geometrical parameters by combining nanofluid on heat transfer and fluid flow characteristics in a helically coiled tube heat exchanger (HCTHE) and demonstrated that certain geometrical parameters such as helix radius and inner tube diameter affected performance of the HCTHE under laminar flow conditions.

Kannadasan et al. [26] compared heat transfer and pressure drop characteristics of CuO/water nanofluids in a helically coiled heat exchanger held in horizontal and vertical positions. The experimental results showed that there was not much difference between horizontal and vertical arrangements in terms of enhancing convective heat transfer coefficient and friction factors of nanofluids compared to water.

The aim of this study was to employ the combination of two passive thermal performance improvement techniques simultaneously (i.e. chaotic advection and nanofluids) in order to maximize advantages of heat transfer enhancement. Accordingly, normal helical coil and chaotic configuration were used. A chaotic coil heat exchanger with no change in axis of coil which was introduced by Tohidi et al. [27] was used in this study. They showed that mixing and heat transfer were significantly increased due to the chaotic advection using Lagrangian tracing of fluid particles and their sensitivity to the initial condition and fluid element calculations. Briefly, in the present work: (i) Heat transfer performance of chaotic and normal coil configurations was compared using water as fluid, (ii) passive heat transfer enhancement-chaotic advection and fluid thermo-physical properties was simultaneously evaluated in coiled tubes filled with nanofluids, and (iii) effects of nanofluids flow in the normal coil and chaotic configuration were analyzed by computing convective heat transfer coefficient and friction factor. Two different nanofluids of water-Al_2O_3 and water-CuO were studied at various nanoparticle concentrations.

2. Coil Geometries

In the present work, chaotic flow was generated using flow inversion phenomenon by assembling two regular coil tubes. The axis of each coil was fixed whereas each 90 degree bend of the chaotic configuration was successively composed of two different pitches with a different length and orientation. This geometrical perturbation was the main cause of flow inversion phenomenon.

Figure (1-a,b) shows one pitch of the two helical coils: one with a clockwise (C.W) pitch b and another with a counterclockwise (C.C.W) pitch b/3. Each bend of the present chaotic configuration (as shown in Figure (1-c)) was successively composed of these two different pitches with a different length and orientation. Consequently, in the chaotic configuration, orientation of the coil changed each 90 degree so that each bend had total pitch b/3. This pattern was periodically repeated in the longitudinal direction. A coil composed of fixed counterclockwise pitch b/3 was employed as the helical coil for comparison.

Both normal and chaotic coil heat exchangers were composed of 10 periods of circular tubes with the same tube diameter, the same unfolded length and heat-transfer surface area. The curvature ratio, defined as ratio of the coil diameter to the pipe, was also fixed. Figure (1-d) demonstrates 10 periods of chaotic configuration, which was used in the simulation.

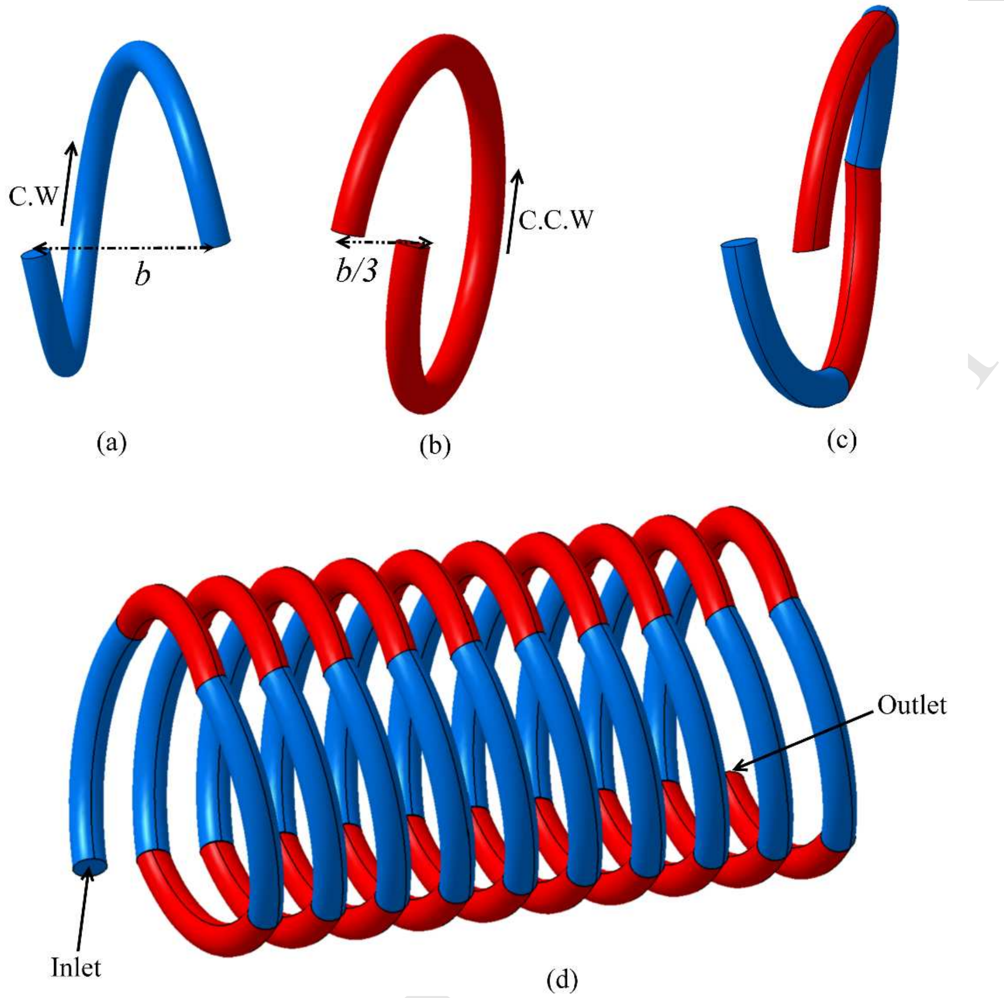

Figure 1. Chaotic coil configuration a) coil with clockwise orientation; b) coil with counterclockwise orientation; c) one period of the chaotic configuration d) 10 periods of the chaotic configuration

3. Governing Equations

In this study, it is assuming nanofluids with low particle volumetric concentration of nanoparticles (less than 3%) as a single phase fluid, there was no agglomeration which occurred inside the coiled tubes. Moreover, this nanofluid was considered incompressible and Newtonian. Fluid flow and convective heat transfer were regarded in the tube, too. In this case, conservative equations of mass, momentum and energy are [28]:

$$\nabla.(\rho_{nf}\mathbf{u}) = 0 \tag{1}$$

$$\nabla.(\rho_{nf}\mathbf{u}\otimes\mathbf{u}) = -\nabla P + \nabla.[\mu_{nf}(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] \tag{2}$$

$$\nabla.(\rho_{nf}c_{p,nf}\mathbf{u}T) = \nabla.(k_{nf}\nabla T) \tag{3}$$

Where ρ_{nf} is the Nano fluid density, **u** is the fluid velocity, P is pressure, μ_{nf} is the dynamic viscosity of the Nanofluid, $c_{p,nf}$ is Nanofluid specific heat and k_{nf} is Nanofluid thermal conductivity

3.1. Thermo-physical properties of Nanofluids

Thermo physical properties of Nanofluids are functions of particle volumetric concentration and temperature. The density of Nano fluid could be given as [28]:

$$\rho_{nf} = \phi\rho_{np} + (1-\phi)\rho_w \tag{4}$$

where ρ_{nf} is the nanofluid density, ρ_w density of water as base fluid, ϕ particle volumetric concentration.

Vajjha and Das [29] determined a correlation for Al_2O_3 and CuO nanofluids. The viscosity correlation final equation used in our numerical computation is

$$\mu_{nf} = \zeta_1 \exp(\zeta_2\phi)\mu_w \tag{5}$$

where $293K \leq T \leq 363K$, $0.01 \leq \phi \leq 0.1$ for Al_2O_3 and $293K \leq T \leq 363K$, $0.01 \leq \phi \leq 0.06$ for CuO and ζ_1 and ζ_2 are constants given in Ref. [23] and μ_w is the base fluid density.

The specific heat of the nanofluids was obtained from the equation given by Xuan and Roetzel [30]:

$$c_{p,nf} = \frac{\phi\rho_{np}c_{p,np} + (1-\phi)\rho_w c_{p,w}}{\rho_{nf}} \tag{6}$$

Where $c_{p,nf}$ and $c_{p,w}$ are specific heat of nanoparticles and water as base fluid respectively.

In this model, thermal conductivity contained both the static part of Maxwell's theory and the dynamic part, considering the Brownian motion of nanoparticles which could be written as [28]:

$$k_{nf} = \frac{k_{np} + 2k_w - 2(k_w - k_{np})\phi}{k_{np} + 2k_w + (k_w - k_{np})\phi} k_w + \varepsilon_1\beta\phi\rho_w c_{p,w}\sqrt{\frac{kT}{\rho_{np}d_{np}}} f(T,\phi) \tag{7}$$

Where d_{np} is the diameter of nanoparticle, ε_1 is a constant for Brownian motion, k_{np} and k_w are thermal conductivities of nanoparticles and water. In this study, the effect of temperature and particle volumetric concentration is accounted in the Brownian motion from the experimental data obtained by:

$$\beta = \beta_1(100\phi)^{\beta_2} \tag{8}$$

$$f(T,\phi) = (c_1\phi + c_2)T / T_0 + (c_3\phi + c_4) \tag{9}$$

where β_1, β_2, c_1, c_2, c_3 and c_4 are constants which are shown in Ref. [23].

3.2. Thermo-Physical properties of base-fluids

Water is selected as the base fluid in this study. Thermo-physical properties of water have been polynomial functions of temperature where the density of water could be written as: [31]

$$\rho_w = -3.570\times10^{-3}T^2 + 1.88T + 753.2 \tag{10}$$

Furthermore, the water viscosity is followed:

$$\mu_w = 2.591\times10^{-5}\times10^{\frac{238.3}{T-143.2}} \tag{11}$$

And water thermal conductivity could be computed by:

$$k_w = -8.354\times10^{-6}T^2 + 6.53\times10^{-3}T - 0.5981 \tag{12}$$

Here the heat specific of water is considered constant at 4200 $Jkg^{-1}K^{-1}$.

3.3. Heat Transfer Relationships

In order to evaluate the amount of heat transfer enhancement, convective heat transfer coefficient is defined as:

$$h = \frac{q_w}{T_w - T_b} \tag{13}$$

Where q_w is the constant heat flux applied to the external wall of the channel, T_w is the wall temperature in each point and T_b is the fluid bulk temperature which is considered:

$$T_b = \frac{\int TudA}{\int udA} \tag{14}$$

Where T is the fluid temperature and u is the axial velocity of the fluid.
The pressure loss is expressed as friction factor which is regarded as:

$$f = \frac{\tau_w}{0.5\rho U_m^2} \tag{15}$$

Where ρ is the fluid density (ρ_w, ρ_{nf}), τ_w is the shear stress on the wall and U_m is the mean velocity.

Reynolds number is explained as:

$$Re = \frac{\rho U_m d}{\mu} \tag{16}$$

where ρ represented fluid density, μ fluid viscosity, d coil pipe diameter and U_m the mean velocity. In order to achieve velocity, pressure and temperature fields, governing equations were solved under 3D and steady assumptions in Cartesian coordinate system which is illustrated in Figure (2). Coil pipe outer diameter and coil radius are 2a and R respectively.

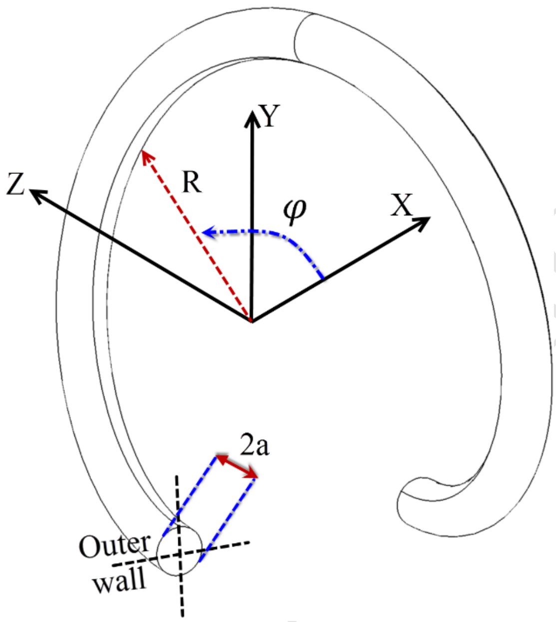

Figure 2. Coordinates of the coil.

4. Boundary Conditions

At the inlet, a fully developed duct flow velocity profiles was used. No slip condition was applied to the pipe wall. Moreover, the heat exchanger wall was supplied by a constant heat flux. At the outlet, however, the pressure and stream wise gradient of the temperature were set at zero. Furthermore, boundary conditions were the same for both configurations. The analyses were conducted for water and nanofluids as the fluid in both geometries for Reynolds numbers between 100 and 500.

5. Numerical Method

The numerical method employed here was finite element method conducted in ANSYS software. Equations of mass, momentum and energy conservation were discretized using a finite element based technique. For obtaining the flow matrices, a segregated algorithm was employed. Therefore, the element matrix was first formed; then, their resultant system was separately solved for each degree of freedom. Galerkin's weighted method was exploited to form integral of elements; meanwhile, method of streamline upwind/Petro-Galerkin (SUPG) was utilized to discretize the advection term. AS equations were coupled, solved by means of intermediate values of other degrees of freedom and then updated after solving each of the equations.

In each iteration, the convergence values were calculated during the simulation process. The convergence was explored for V_x, V_y and V_z as velocity and P as pressure. The convergence criterion in this solution was considered 10e-8. For discrediting the governing equations, an O-grid mesh was consumed. Figure 3 shows the mesh topology used in one cross-section.

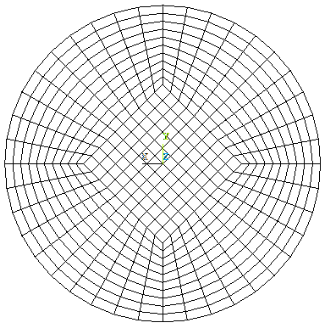

Figure 3. Grid on one cross-section of the helical pipe

5.1. Mesh independence tests

Mesh independence tests were carried out for four structured mesh configurations. For all mesh configurations, convective heat transfer coefficient and friction factors were computed using equations (13) and (15) and then compared. Table (1) summarizes results for the convective heat transfer coefficient and the friction factors for various mesh configurations which h_w and f_w are convective heat transfer coefficients and friction factor of water and h_{nf} and f_{nf} are convective heat transfer coefficient and friction factor of nanofluids flow. Mesh configuration contains number of elements in cross-section and axial length of coil which is shown as (cross-section$\times$axial length) in Table (1). Based on these results, there was no significant difference between numerical calculations and deviations were below 1%. Therefore, the smaller mesh configuration (500×640) was chosen to perform calculations.

Table 1.Grid independence test for water and nanofluid flow with 1% concentration at Re=300.

Mesh Configuration	500×640	605×640	500×712	605×712
$h_w[W.m^{-1}.K^{-1}]$	360.9146	361.1672	361.2394	361.1311

f_w	0.05284	0.05288	0.05334	0.05318
$h_{nf}\,(CuO-Water)\,[W.m^{-1}.K^{-1}]$	384.47	387.47	387.89	386.66
$f_{nf}\,(CuO-Water)$	0.05406	0.05451	0.05410	0.05440
$h_{nf}\,(Al_2O_3-Water)\,[W.m^{-1}.K^{-1}]$	381.94	382.26	385.57	384.65
$f_{nf}\,(Al_2O_3-Water)$	0.05398	0.05440	0.05446	0.05401

5.2. Model Validation

In this paper, to predict the enhancement of heat transfer for nanofluids in the proposed chaotic coil configuration, the present CFD computation technique was verified comparing the literature values. The considered nanofluids model is confirmed with an experimental study of nanofluid heat transfer conducted by Anoop et al. [32]. The heat transfer performance of nanofluid flows in a circular tube of 4.75×10^{-3} m diameter and 1.2 m length was approximated with 2D axisymmetric model. At the beginning, the heat transfer performance of water flow with a Re number of 1,580 is considered for checking validity; then, the heat transfer performance of water-Al_2O_3 nanofluid of 4 wt.% with nanoparticles of 45 nm flowing with a Re number of 1588 is compared to the previous one, shown in Figure (4). A good agreement is found between the model predictions and the heat transfer performance from experiments for both water and nanofluid.

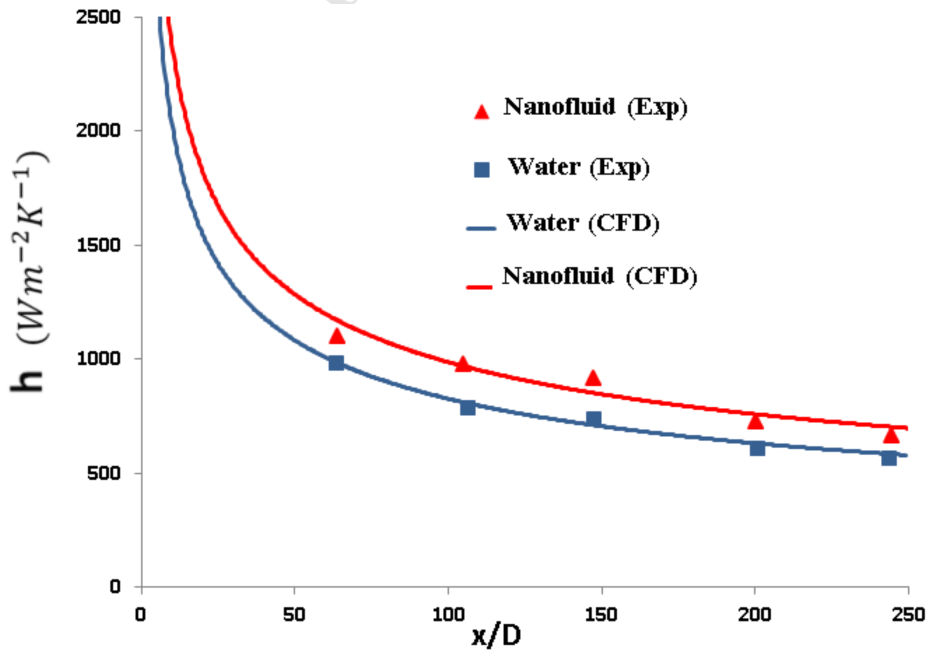

Figure 4. Comparison of heat transfer coefficient between simulation and experimental data [32] for both water and nanofluid.

6. Effects of chaotic advection

In order to analyze effects of chaotic advection on heat transfer, performance of the chaotic and normal coils was estimated by computing convective heat transfer coefficient (h) and friction factor (f) while water was the studied fluid. Also, the flow and temperature fields were compared in the normal and chaotic coil configurations.

The geometrical perturbation in the chaotic coil configuration led to reorientation of flow after each 90 degree coil bend. Direction changes of the flow after each 90 degree bend resulted in movement of fluid particles in radial direction. Therefore, mixing and heat transfer were increased in radial direction. Figure (5) shows isotachs velocity contours of the chaotic and normal coil flows for different φ values. Figure (5-a) presents development of velocity contours in the helical coil. Since the fluid entered in helical pipe with fully developed profile, the velocity fields were the same at each cross-section. The velocity field was characterized by two longitudinal Dean-type vortices and the axial velocity contours showed the C-shape. Maximum velocity was shifted towards outer wall of the helical coil.

As seen in Figure (5-b), maximum value of velocity contour in the chaotic flow periodically shifted to the left and right after each 90 degree bend, which led fluid particles to escape from Dean-roll-cells and caused movement in radial direction. This phenomenon resulted in improved mixing and enhanced heat transfer.

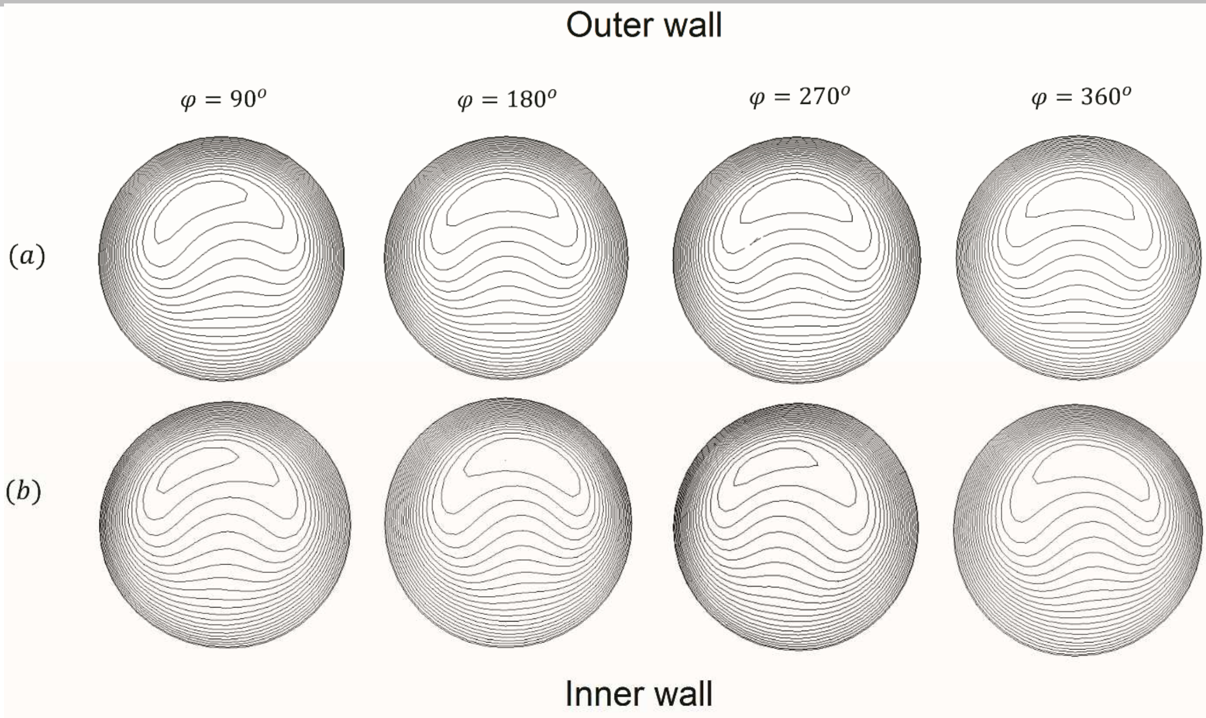

Figure 5.Velocity contours at different cross-sections in a) normal coil and b) chaotic coil at Re=300

Figure (6) illustrates development of velocity profiles at different cross-sections in the normal and chaotic coils. Velocity profile in the normal coil flow became symmetric and location of its maximum values did not change by increasing φ values. The flow direction change caused asymmetric velocity profile in the chaotic flow and its maximum values periodically shifted to the left and right after each bend. The results revealed that velocity contours, which had maximum value in each bend, were not maximum after the next bend. Therefore, radial mixing between fluid elements was much higher than that of normal coil.

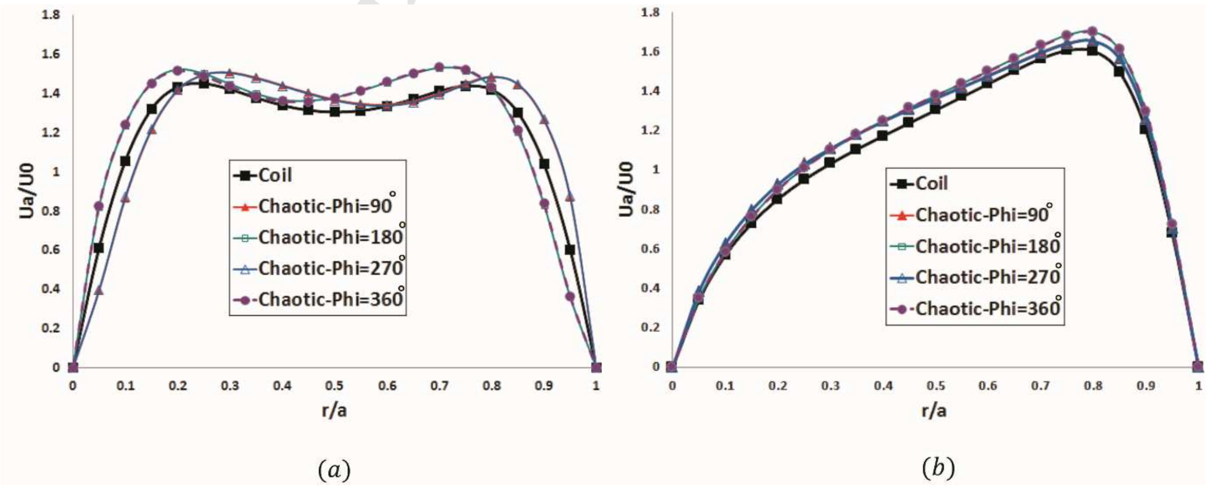

Figure 6. Axial velocity profile in coil and chaotic configuration on a) horizontal and b) vertical centerline at Re=300

The heat transfer in the chaotic configuration was higher than the normal helical coils. Thermal development study was carried out under constant heat flux condition. Figure (7) demonstrates temperature contours at different cross-sections for the chaotic and normal coil flows. As seen in Figure (7-a), high temperature zones shifted to the outer side in the normal coil because of centrifugal force. The identical patterns of temperature development at various axial cross-sections demonstrated the relationship between temperature fields and fluid mechanics of the systems. Velocity field was fully developed; therefore, after a very short distance from the tube inlet, the temperature profiles in the coiled tube became similar.

Figure (7-b) shows temperature contours at different cross-sections for the chaotic coil flow. Dean-roll-cells were broken and reassembled after each 90 degree bend. Therefore, fluid particles entered new Dean-roll-cells with different shapes and directions and their trajectories covered the area of cross-section.

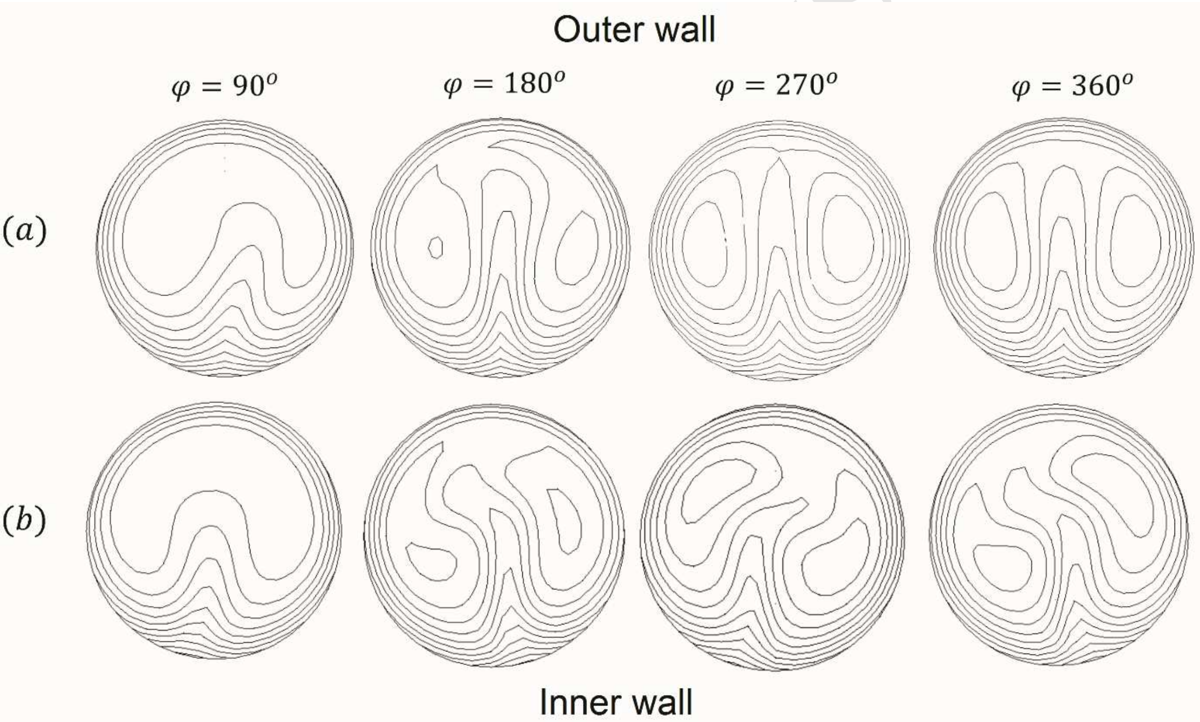

Figure 7. Temperature contours at different cross-sections in a) normal coil and b) chaotic coil at Re=300

Development of temperature profiles at different cross-sections is shown in Figure (8). As observed in Figure (8-a), numerical calculations showed that temperature profile on horizontal centerline became asymmetric in chaotic flow because of C.W and C.C.W changes in the flow direction after each 90 degree bend. Figure (8-b) shows temperature profile on vertical centerline of the normal and chaotic coils, implying major changes in the profile in the chaotic coil at different cross-sections.

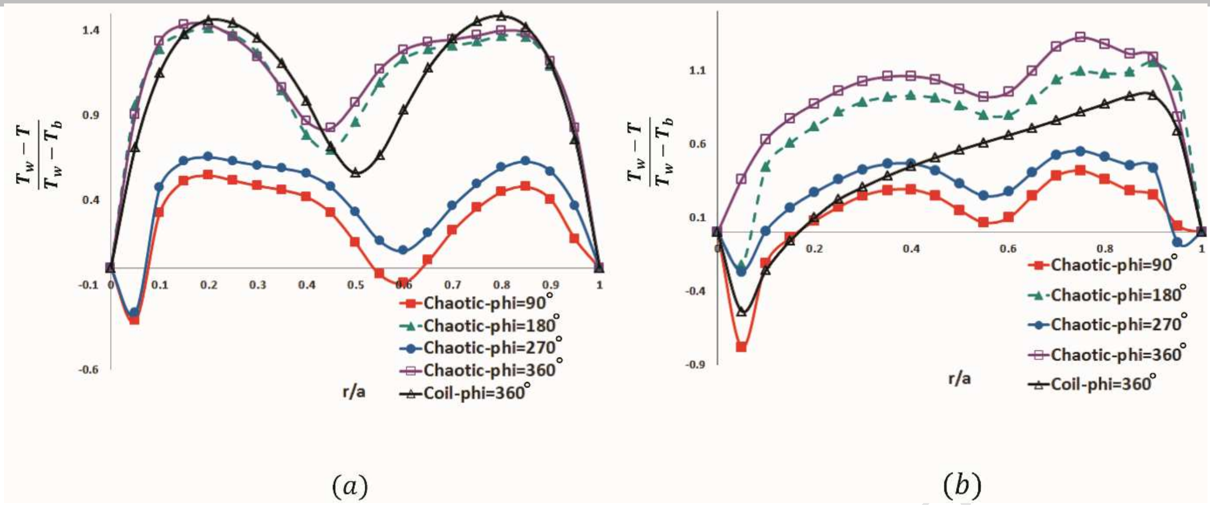

Figure 8. Non-dimensional temperature profile in coil and chaotic configuration on a) horizontal and b) vertical centerline at Re=300

In order to compare heat transfer performance of the chaotic and normal coils, the convection heat transfer coefficient and pressure loss in terms of friction factor were calculated. Figure (9) displays variation of h versus Re for chaotic and normal coil configurations. Each bend of the chaotic configuration was composed of two different pitches with a different length and orientation. Therefore, chaotic flow was disturbed after each 90 degree bend, one of which had a clockwise (C.W) pitch P and another had a counterclockwise (C.C.W) pitch P/3. This perturbation could overcome poor mixing due to Dean-roll-cells in radial direction and significant enhancement in heat transfer was obtained in the chaotic flow.

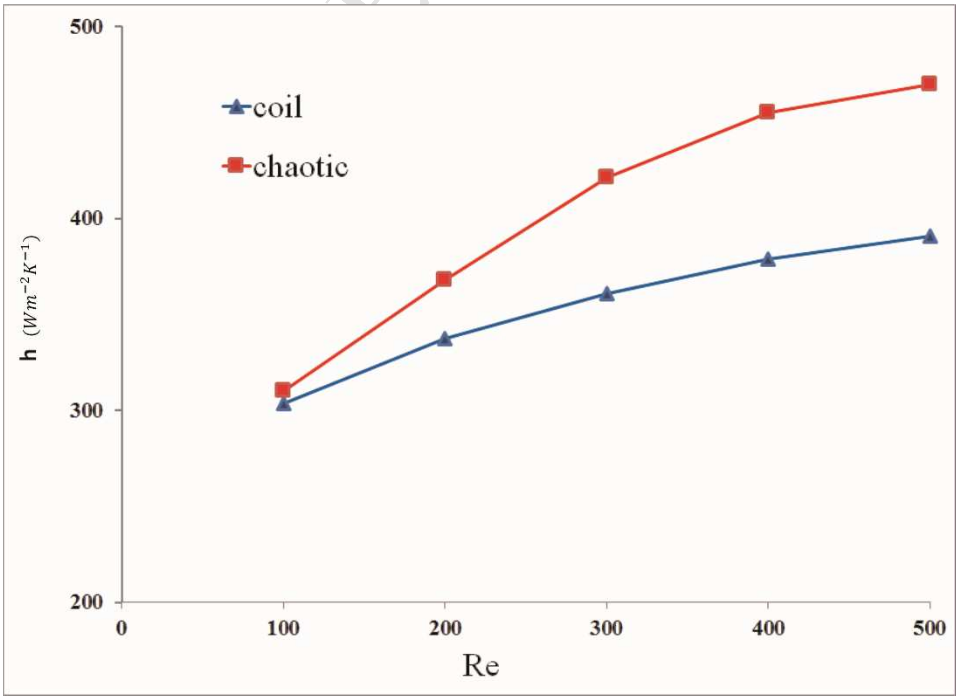

Figure 9. h variations with Re for two geometries

Pressure loss increment in chaotic flow is depicted in Figure (10). Flow direction changes after each 90 degree bend in the chaotic configuration resulted in pressure loss increases compared to the normal coil. Since both heat transfer and pressure loss raised in the chaotic coil in order to compare thermal performance of two heat exchangers, h/f ratio was calculated. Figure (11) shows h/f with Re for both heat exchangers. Numerical results revealed that pressure loss growth was higher than heat transfer increment in chaotic flow at lower Reynolds number; but, by increasing Reynolds number, thermal performance (h/f) significantly improved in the chaotic flow. Global heat-transfer measurements showed that the chaotic heat exchanger was more efficient than the helical one; with heat transfer enhancement of 3 to 17% and 7–9% relative pressure drop.

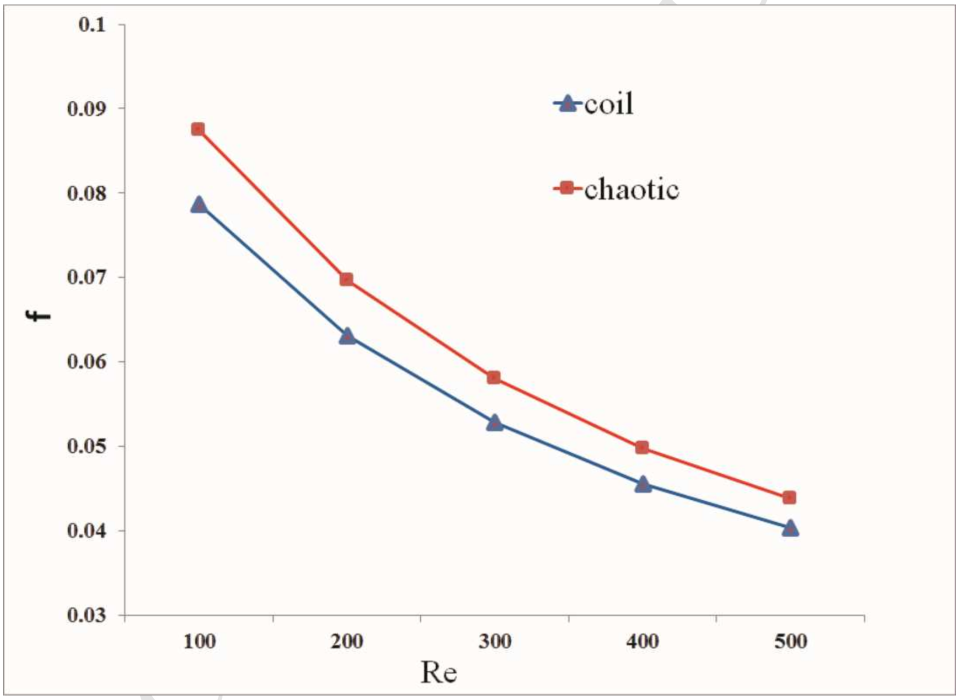

Figure 10. f variations with Re for two geometries

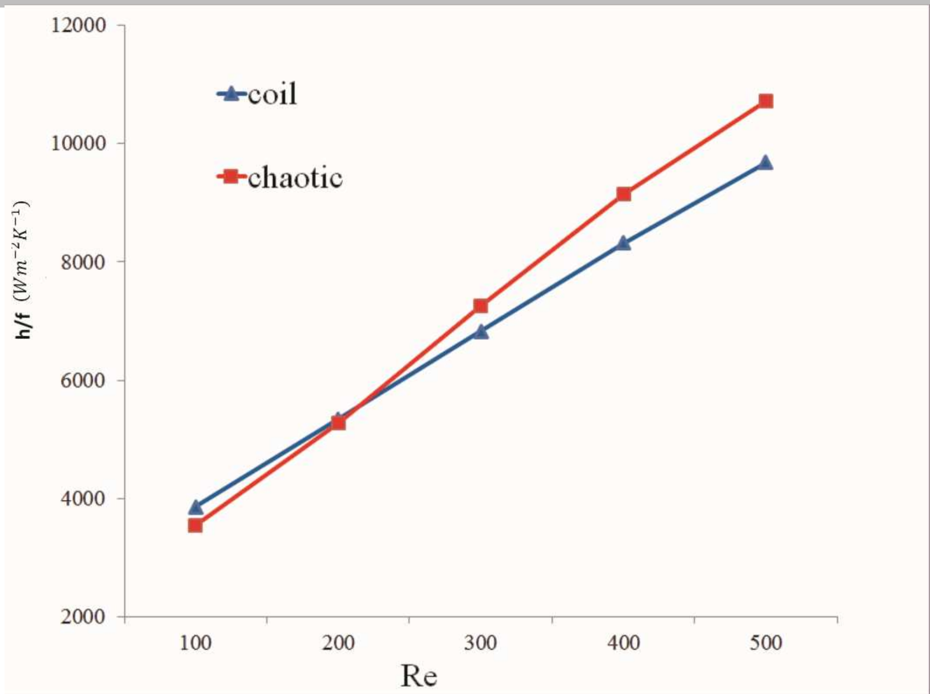

Figure 11. h/f variations with Re for two geometries

7. Effect of Nanofluids

To analyze effects of nanofulids on heat transfer in a chaotic coil, two types of nanofluids (Al_2O_3 and CuO) flow with 1-3% particle volumetric concentrations were simulated in both geometries. Effect of type and concentration of nanofluids are separately discussed.

7.1. Nanoparticles concentration

In an earlier study [23], it was shown that, at various concentrations of Al_2O_3 nanofluid, there was no significant difference in secondary flow development inside the normal coil.

Figure (12) shows velocity contours of Al_2O_3 nanofluid flow in the chaotic coil at different cross-sections. The results revealed that increase in concentration of nanofluid particles did not have an impressive effect on velocity contours and their shape and direction did not change. Therefore, velocity profiles remained the same and their trend did not have major changes by increasing concentration.

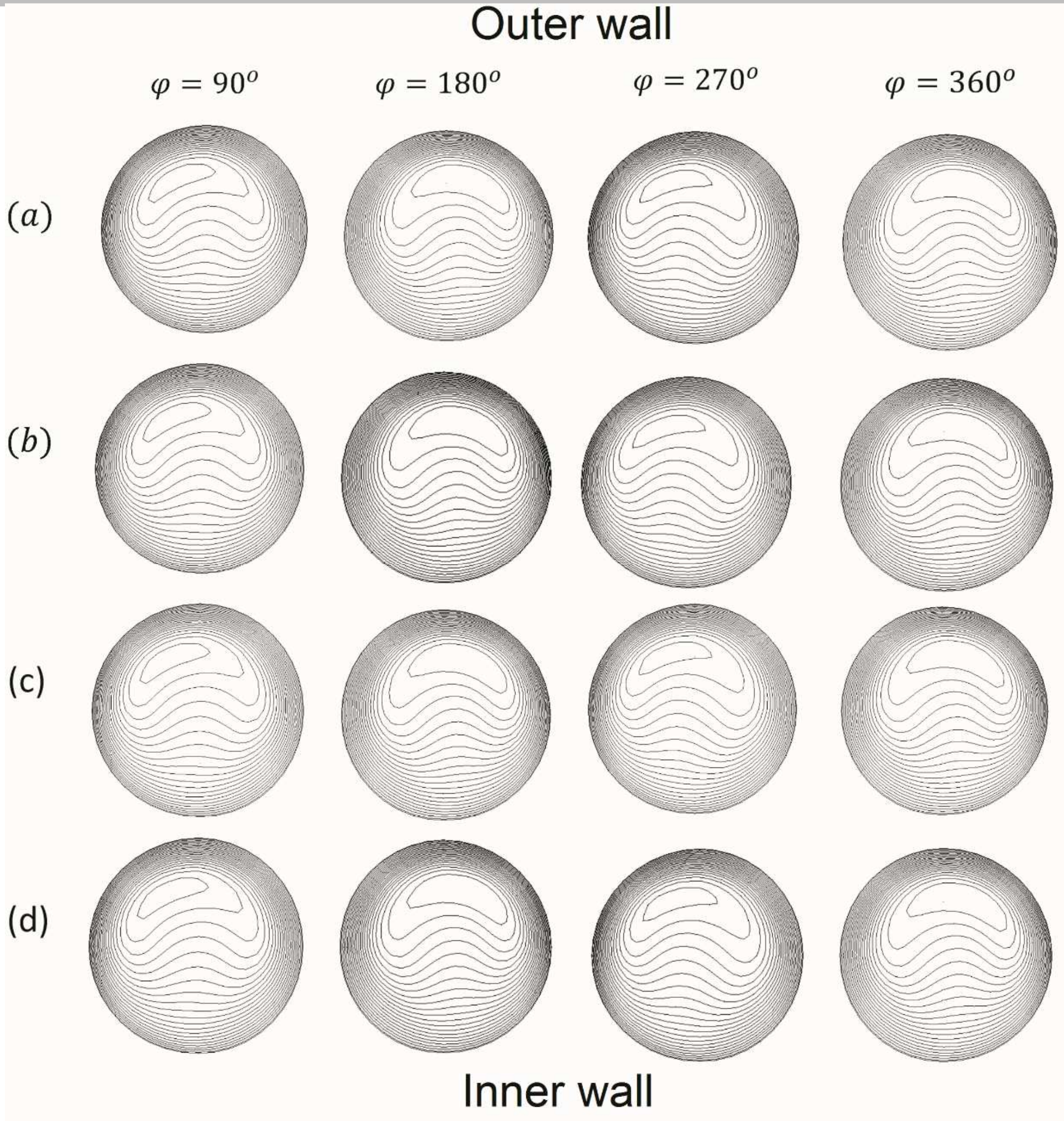

Figure 12. Development of velocity contours for Al_2O_3 nanofluid flow with a) 0%, a) 1% c) 2% d) 3% concentration in the chaotic coil at Re=300.

Figure (13) shows temperature contours of nanofluid flows in the chaotic coil, demonstrating that change of concentrations of nanofluids had minor effects on temperature contours. Dean-roll-cells had an identical shape at all particle volume concentrations and therefore there were minor changes in temperature profiles.

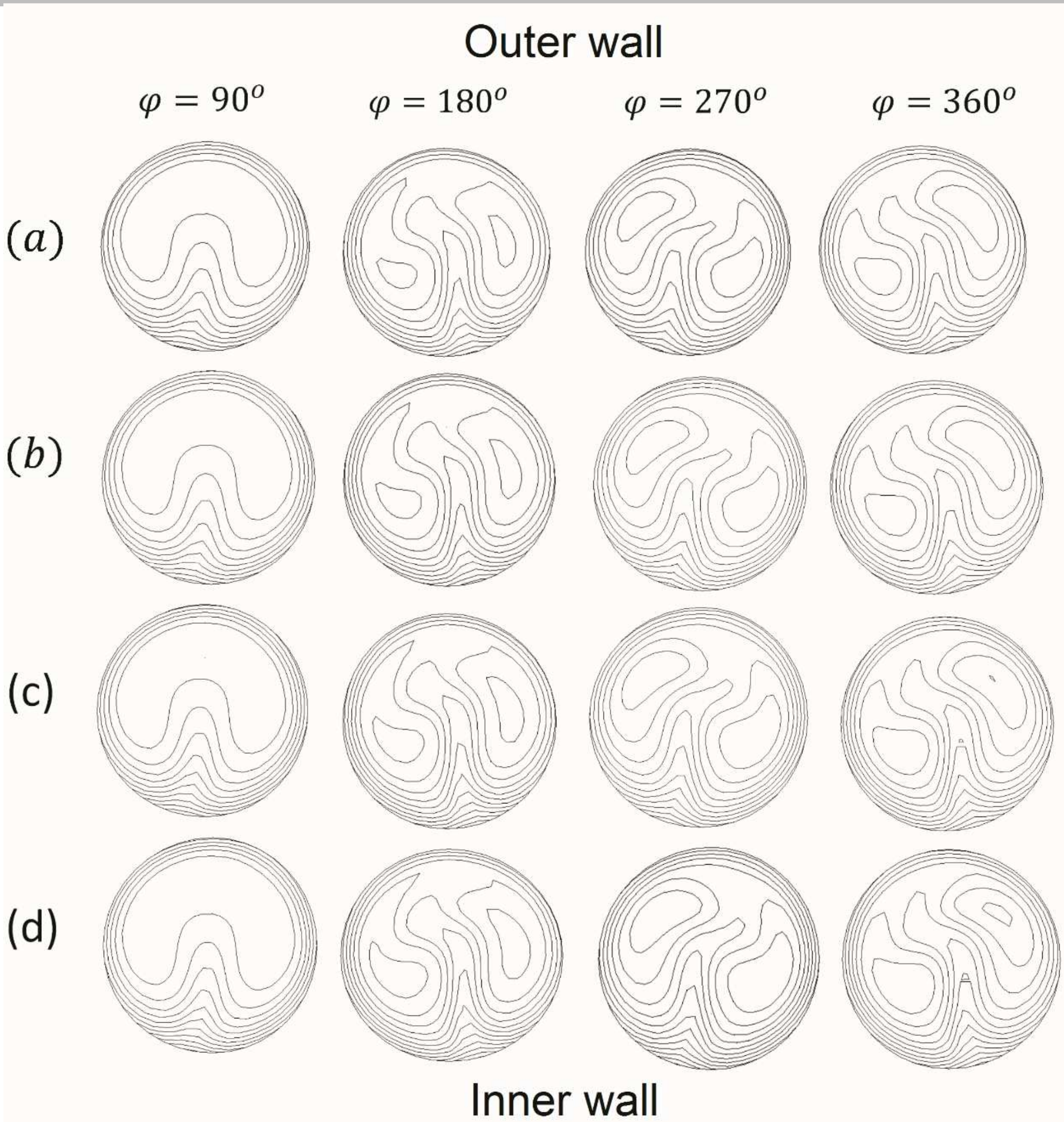

Figure 13. Development of temperature contours for Al_2O_3 nanofluid flow with a) 0%, a) 1% c) 2% d) 3% concentration in the chaotic coil at Re=300.

Variations of h versus Re for both coils are given in Figure (14). As is evident, addition of 1-3% nanoparticles resulted in 4-10%, 6-12% and 7-13% improvement in heat transfer in the normal coil for Al_2O_3 nanofluid and 5-12%, 6-13% and 7-14% for CuO nanofluid, respectively, compared to the base fluid while, in the chaotic configurations, heat transfer enhancement was 10-11%, 9-11% and 11-13% for Al_2O_3 nanofluid and 6-12%, 11-13% and 13-16% for CuO nanofluids, respectively.

Numerical calculations showed that heat transfer of nanofluid flow with 1-3% nanoparticle volumetric concentrations in the chaotic configuration increased by 2-18%, 2-19% and 3-21% for Al_2O_3 nanofluid compared to the normal helical coil flow. Heat transfer improvement was 2-18% and 3-21% in the case of 3-25% for CuO nanofluid.

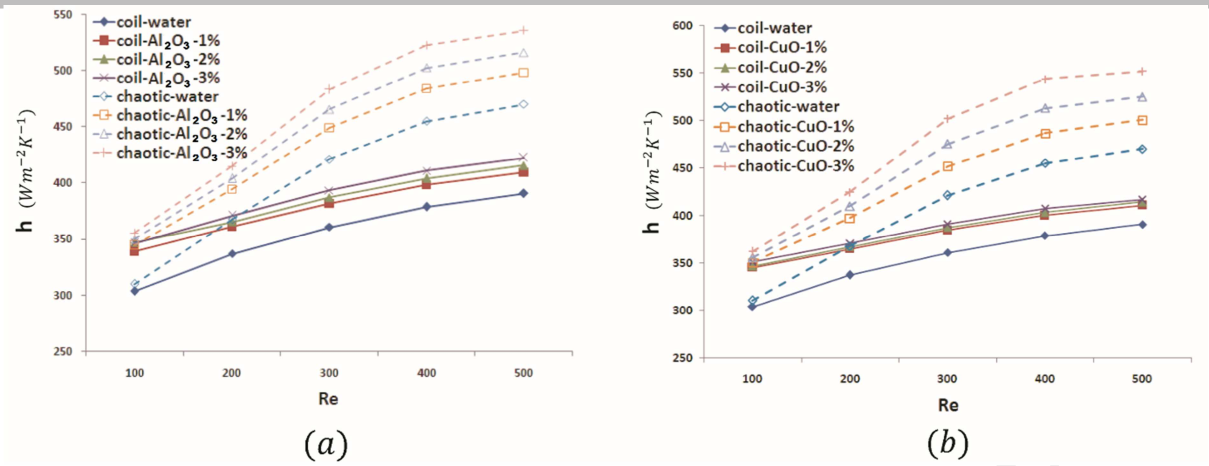

Figure 14. h variations with Re for (a) Al_2O_3 and (b) CuO nanofluids flow with 1-3% concentrations

Figure (15) represents variation of friction factor versus Reynolds number for both normal and coil chaotic configurations. As seen in Figure (15), friction factor raised for both types of nanofluids in the chaotic coil compared with normal coil. These results revealed that 1-3% concentration of nanofluid particles increased by 2-4%, 4-12% and 6-18% in friction factor in the normal coil for Al_2O_3 nanofluid and 2-4%, 4-13% and 13-18% for CuO nanofluid, respectively. In the chaotic configurations however, friction factor increased by 2-4%, 3-8% and 5-12% for Al_2O_3 nanofluid and 2-4%, 4-11% and 6-18% for CuO nanofluids, respectively, compared with water as base fluid.

Geometrical perturbations in the chaotic coil increased pressure loss and numerical calculations meant that heat transfer of nanofluid flow containing 1-3% nanoparticle in the chaotic configuration increased by 8-10%, 8-19% and 3-21% for Al_2O_3 nanofluid compared to the normal coil flow. Heat transfer improvement was 2-18%, 3-21% and 3-25% for CuO nanofluid.

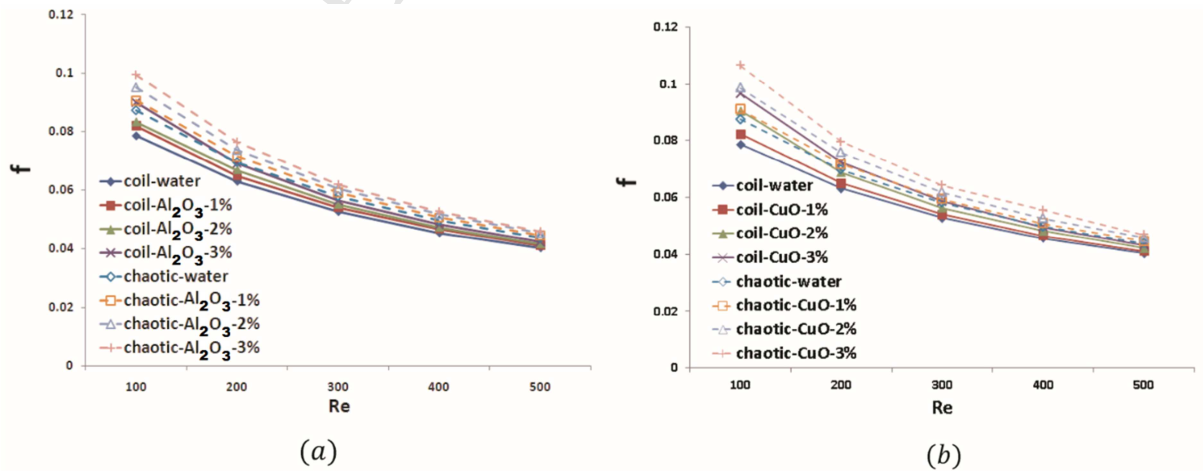

Figure 15.f variations with Re for (a) Al_2O_3 and (b) CuO nanofluids flow with 1-3% concentrations

In order to compare thermal performance of both heat exchangers, variations of h/f versus Re are plotted in Figure (16). Thermal performance in the normal coil decreased by increasing nanofluid concentration and, in both nanofluids flow in the normal coil with 3% concentration, pressure loss was higher than heat transfer enhancement, demonstrating a limitation to use nanofluids in the coiled tubes. According to the presented results, nanofluid with 1% concentration was the best choice among the investigated models (1-3% nanoparticle volumetric concentration) in terms of enhancing thermal performance of normal coiled tubes.

At lower Reynolds number, higher friction factor in the chaotic coil resulted in lower thermal performance of chaotic coil compared to normal coil with nanofluid flow; but, with increasing the Reynolds number and volumetric concentrations of nanoparticles, heat transfer significantly improved in the chaotic coil with marginal increase in pressure loss.

As seen in Figure (16), heat transfer rate in the chaotic coil profoundly raised while pressure loss increment by Reynolds number increase was negligible. Therefore, there was no limitation in utilizing nanofluid with concentration of higher than 1% in the chaotic coil. However, growth in pressure loss due to higher nanofluid concentration caused small improvement in thermal performance with increasing volumetric concentration of nanoparticles.

The significant consequence of numerical calculations was higher than water heat transfer as fluid in the chaotic coil rather than that of nanofluids at various concentrations in the normal coil, which implied high rate of heat transfer in the chaotic configuration. Since thermal performance of chaotic coil with water as fluid was higher than normal coil with nanofluids, adding nanofluids in the chaotic coil resulted in significant enhancement of heat transfer.

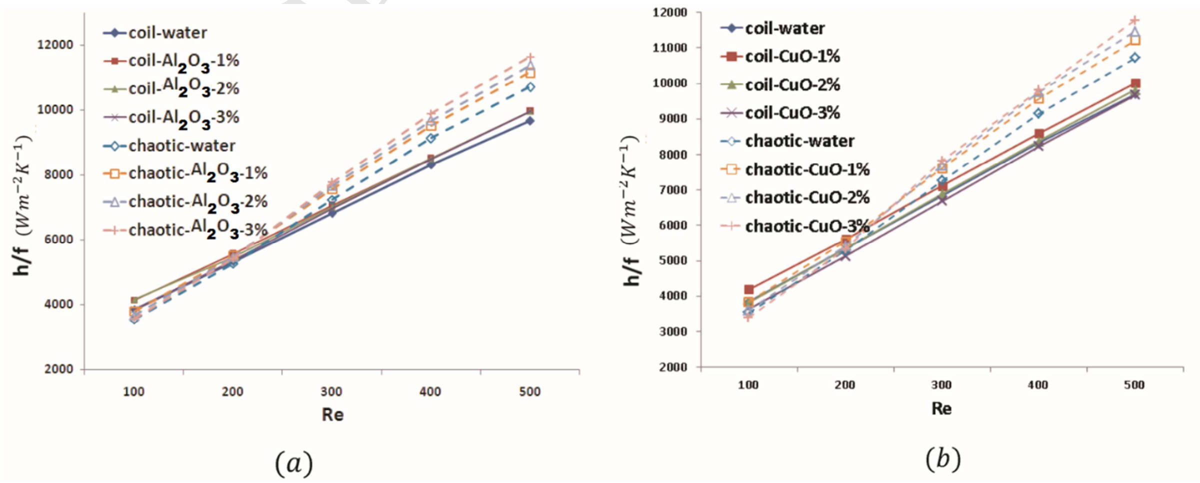

Figure 16. h/f variations with Re for a) Al_2O_3 and b) CuO nanofluids flow with 1-3% concentration

7.2. Effect of Nanoparticles Type

To investigate effects of nanofluids type on thermal performance of heat exchangers, performances of water-Al_2O_3 and water-CuO nanofluids were compared. Figure (17) illustrates h versus variation with Re for both normal and chaotic coils as well as different nanofluid concentrations.

Clearly, applying CuO nanofluid to both normal and chaotic coils led to more increase in heat transfer than Al_2O_3 nanofluid. There was more difference between CuO and Al_2O_3 nanofluids in terms of heat transfer enhancement in the chaotic coil; meaning that CuO nanofluid flow with 3% concentration in the chaotic coil had the highest rate of heat transfer among the investigated models.

No significant difference was observed between two types of nanofluids in the normal coil. Moreover, heat transfer rate in the normal coil increased by 1% maximum for CuO nanofluid with 1-3% concentration compared with Al_2O_3 nanofluid. Heat transfer enhancement, on the other hand, was 0.5-1.6%, 1.4-2% and 1.6-4% for CuO nanofluid with 1-3% concentration, respectively, compare to Al_2O_3 nanofluid in the chaotic coil.

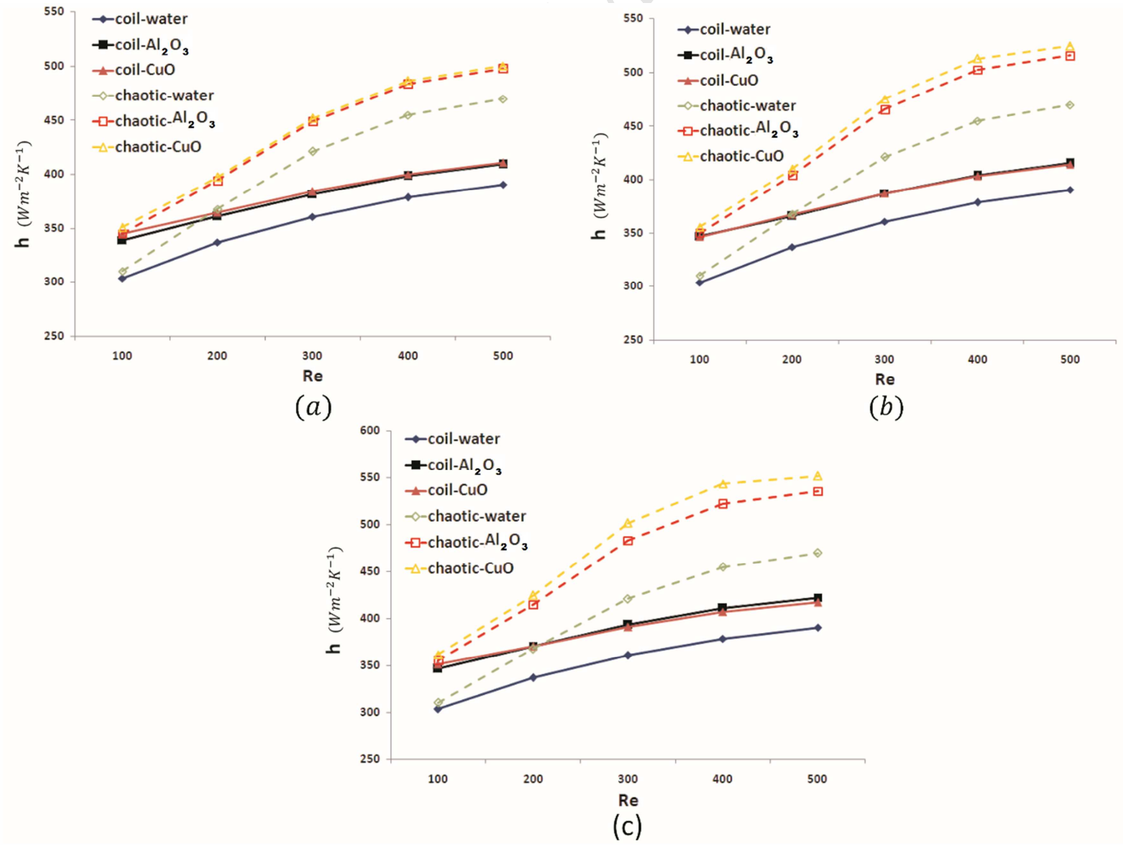

Figure 17.h variations with Re for a)1%, b)2% and c)3% concentrations of Al_2O_3 and CuO nanofluids flow

Figure (18) presents apparent variation of f versus Re for nanofluids flow with different concentrations in both chaotic and coil configuration. Friction factor for Al_2O_3 nanofluid flow increased by 0.09-0.25%, 1.1-3.3% and 1.9-6.6% for 1-3% concentration, respectively, compared with CuO nanofluid in the normal coil. Also the numerical results showed 0.09-0.27%, 1.1-3.4% and 1.8-6.5% increase in friction factor for Al_2O_3 nanofluid compared to CuO nanofluids with 1- 3% concentration, respectively in the chaotic coil.

Clearly, friction factor for both types of nanofluid in the chaotic coil was higher than that in the normal coil. Higher friction factor suggested greater pressure loss and pumping costs as a result of geometrical perturbation in the chaotic coil. It seems that both types of nanofluid had almost the same friction factor in the normal and also chaotic coils.

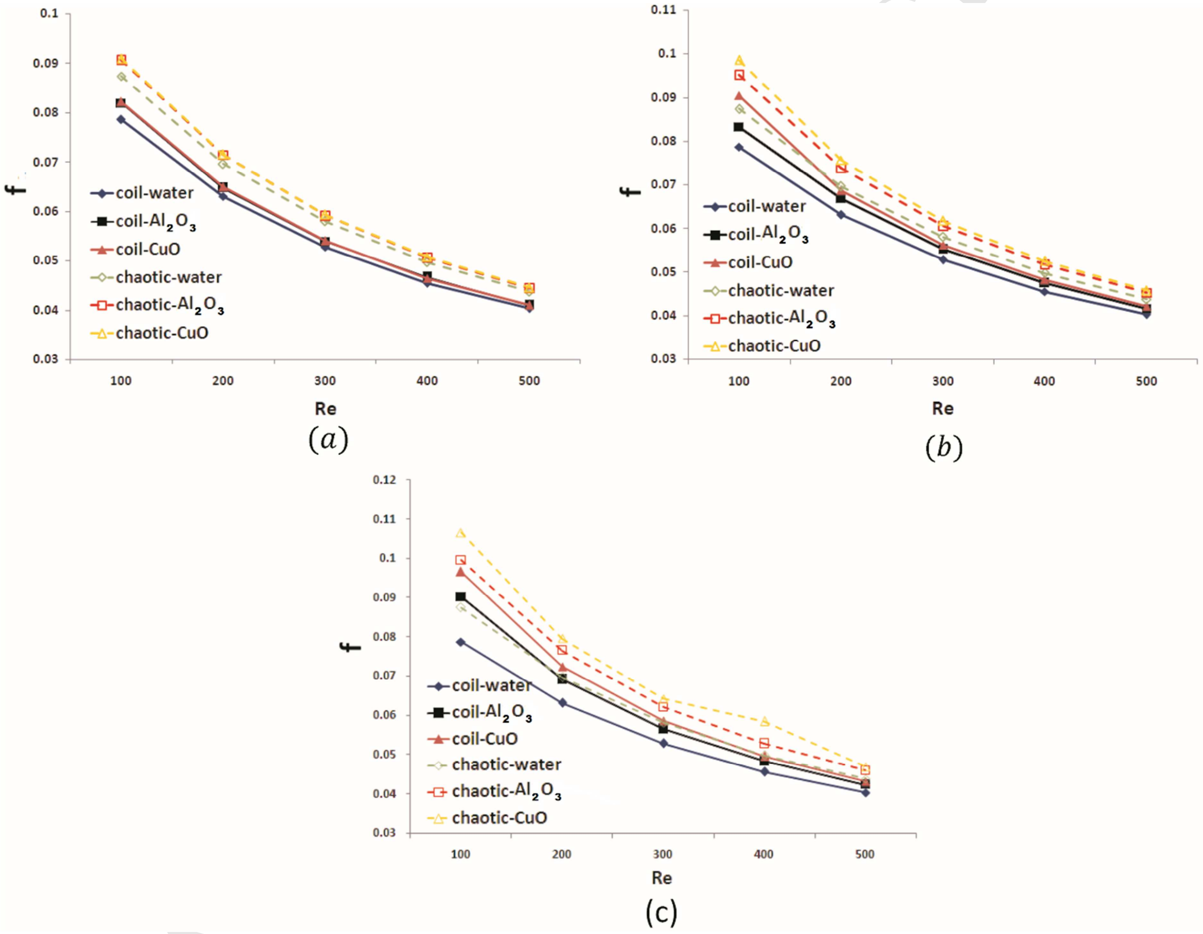

Figure 18. f variations with Re for a) 1%, b) 2% and c)3% concentrations of Al_2O_3 and CuO nanofluids flow

Variation of h/f with Re is plotted in Figure (19) for different concentrations of nanofluid. Thus, thermal performance of CuO nanofluid was greater than that of Al_2O_3 nanofluid in both normal and chaotic coils.

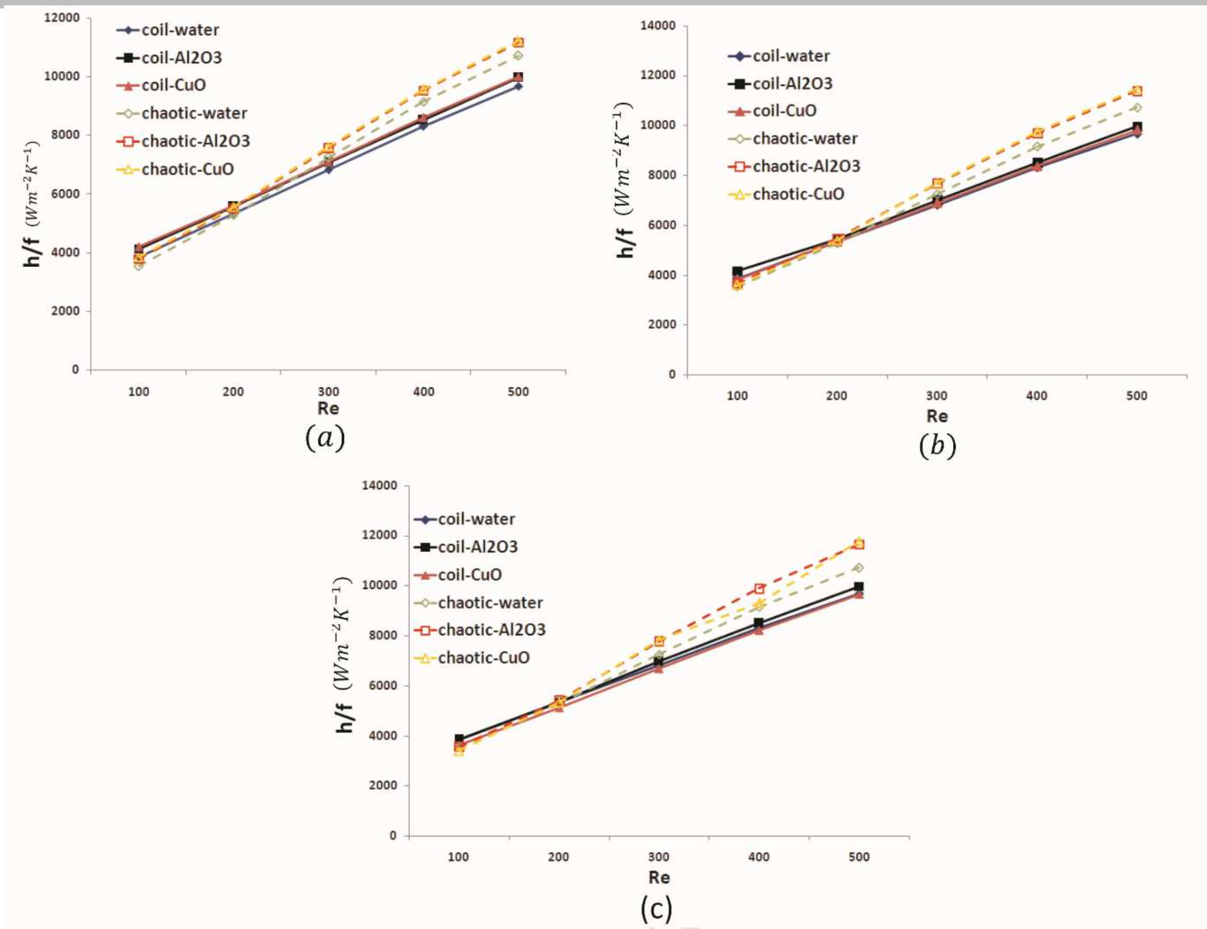

Figure 19.f variations with Re for a)1%, b)2% and c)3% concentrations of Al2O3 and CuO nanofluids flow

8. Conclusion

The present work investigated two passive techniques for heat transfer improvement (chaotic advection and nanofluids) in both separated and coupled ways in coiled heat exchangers. Centrifugal force led to generation of a pair of vortices called Dean-roll-cells, which essentially trapped fluid particles and caused reduction in heat transfer and decrease in radial direction due to poor mixing. The chaotic coil configuration was composed of two coils with C.W and C.C.W flow directions at each 90 degree bend. Reorientation of coil flow causes Dean-roll-cell break-up which reassemble after each 90 degree bend. Therefore, fluid particles could radially move and enhance heat transfer. Although nanofluid flow in coil increased rate of heat transfer, it could not overcome poor mixing due to Dean-roll-cells; chaotic advection with nanofluids increased heat transfer. Reorientation of flow in the chaotic configuration resulted in uniform distribution of nanoparticles in the whole area of cross-section of the coiled pipe.

Two types of nanofluids (water-CuO and water-Al_2O_3) were investigated at various particle volumetric concentrations. A significant outcome can be summarized that thermal performance of chaotic coil with water as fluid is higher than that in a normal coil with nanofluids; hence, adding nanofluids in the chaotic coil resulted in significant enhancement of heat transfer. According to the numerical results, only 1% of both types of (Cuo and Al_2O_3) nanofluids in a chaotic configuration considerably increased heat transfer. Heat transfer improvement increased with higher concentration of nanofluid particles.

Brownian motion has been proposed by various researchers as one of the important factors in heat transfer enhancement. Since random motion of particles may lead to reduced thickness of thermal layer, it could improve heat transfer. Although homogeneous single phase model used in this paper cannot identify Brownian motion of the nanoparticles, a thermal conductivity correlation was employed which considered effects of Brownian motion. These effects will be studied in future works.

Finally, results of thermal performance in two coil configurations could be summarized as below:

Chaotic flow (water-CuO) > Chaotic flow (water-Al_2O_3) > Chaotic flow (water) > Normal coil flow (water-CuO) > Normal coil flow (water-Al_2O_3) > Normal coil flow (water)

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